Relativistic description of Meson-Exchange Currents and SuperScaling predictions in charged-current neutrino reactions

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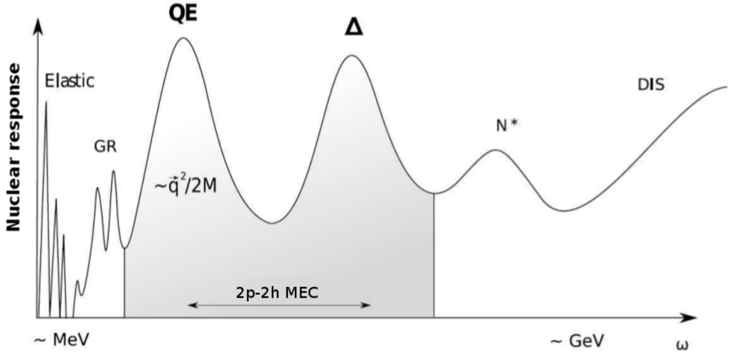
Nuclear response in terms of the energy transfered



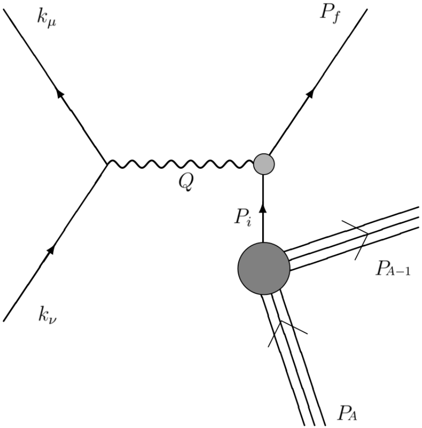
Quasielastic Regime

CCQE scattering

$\nu_\mu(\bar{\nu}_\mu)+A \to \mu^-(\mu^+)+p(n)+(A-1)$

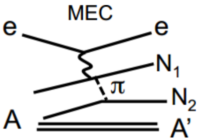
Impulse Approximation (IA)

The neutrino only interacts with a single bound nucleon.

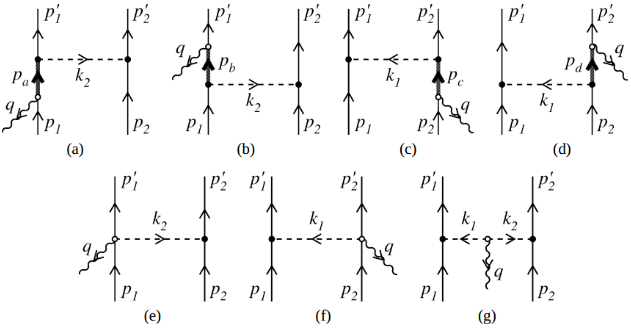


2p-2h MEC contributions

➠ A weak boson from the leptonic current is exchanged by a pair of nucleons (2-body current) ⇒ 2-nucleon emission from the primary vertex.
➠ 2p-2h effect dominated by the meson exchange current (MEC).



Over 100,000 terms are involved in the calculation, with seven-dimensional integrations



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Experimental status

2p-2h effects on the experimental side

- Recent ν-CCQE measurements have reported a large M_A value, in disagreement with the standard estimations $\Rightarrow$ Explanation: events interpreted as CCQE are in fact due to a different dynamical mechanism $\Rightarrow$ multinucleon emission (2p-2h MEC, correlations, etc).
- Understanding of the 2p-2h effect is an urgent program in neutrino interaction physics for current and future oscillation experiments $\Rightarrow$ World wide efforts to model and implement this process in neutrino interaction simulations.
- The importance of MEC is well known from electron scattering data $\Rightarrow$ Despription of the dip region between the QE and the Δ peak. The contribution of MEC is larger in the transverse response than the longitudinal one $\Rightarrow$ ν-CCQE(Transverse)$\gg$ ν-CCQE(Longitudinal).
- The relevance of this process in neutrino interactions was first pointed out after the first MiniBooNE results.

Briefly description of 2p-2h MEC models

✪ Discrepancy between the MiniBooNE data and traditional QE nuclear models $\Rightarrow$ nuclear correlations, final-state interactions, and meson-exchange currents (MECs) may play an important role.
✪ Recent theoretical calculations have stressed the importance of multinucleon knockout and MECs contributions in neutrino QE scattering.
✪ 3 microscopic models based on RFG predicting multinucleon knockout effects QE $\nu-{}^{12}$C cross sections:

Model	Relativistic	Including
Martini	Based on a non-Rel. model with Relativistic ingredients	MEC and pionic correlation diagrams. Direct-exchange interference neglected
Nieves	Some kinematical approximations in the WNNπ vertex	Momentum of the nucleon in the WNNπ vertex fixed. Direct-exchange interference neglected
SuSA	Fully Relativistic	2p-2h MEC but not correlations. Including all interference terms (7D integration)

Martini et al. PRC81, 045502 (2010) **Nieves et al.** PRC83, 045501 (2011)
SuSA model PRD90, 033012 (2014); PRD91, 073004 (2015)

Contents

Theoretical description: CCQE ν-nucleus cross section

Double differential cross section

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right]_\chi = \sigma_0 \mathcal{F}_\chi^2 \quad ; \quad \sigma_0 = \frac{\left(G_F^2 \cos\theta_c\right)^2}{2\pi^2}\left(k_\mu \cos\frac{\tilde{\theta}}{2}\right)^2 \quad ; \quad \chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$$

Nuclear structure information

$$\mathcal{F}_\chi^2 = \hat{V}_L R_L + \hat{V}_T R_T + \chi\left[2\hat{V}_{T'} R_{T'}\right]$$

$$\hat{V}_L R_L = V_{CC} R_{CC} + V_{CL} R_{CL} + V_{LL} R_{LL}$$

$L \to (\mu\nu) = (00, 03, 30, 33)$;

$T \to (11, 22)$; $T' \to (12, 21)$

Leptonic (j^μ) & hadronic currents (J^μ)

$$j^\mu = j_V^\mu + j_A^\mu \quad ; \quad J^\mu = J_V^\mu + J_A^\mu$$

Rosenbluth-like decomposition

$$R_L = R_L^{VV} + R_L^{AA} \qquad R_{T'} = R_{T'}^{VA}$$

$$R_T = R_T^{VV} + R_T^{AA}$$

Weak nuclear current

$$J_V^\mu = \bar{u}(P')\left[F_1^V \gamma^\mu + \frac{i}{2m_N} F_2^V \sigma^{\mu\nu} Q_\nu\right] u(P)$$

$$J_A^\mu = \bar{u}(P')\left[G_A \gamma^\mu + \frac{1}{2m_N} G_P Q^\mu\right] u(P)$$

Nuclear responses

Composed of VV (vector-vector), AA (axial-axial) and VA (vector-axial) components arising from the V and A weak nuclear currents.

Theoretical description: Nuclear model dependence

➠ For this purpose we need to employ a nuclear model which can be applied up to very high energies.

➠ Two basic requirements: it has to be relativistic and it must describe QE electron scattering data from intermediate up to high energies.

SuperScaling Approach (SuSA)

- Based on the superscaling function extracted from QE electron scattering data.
- **Scaling**: The response of a many-body system ***scales*** when it can be described in terms of a particular combination of two variables, called ***scaling variable*** $\psi(\omega, q)$.
- In lepton-nucleus scattering, nuclear effects can be analyzed through a **Scaling Function** $f(\psi)$ constructed from the ratio between the QE cross section and the proper single-nucleon one.

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Theoretical description: Scaling phenomenon

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \quad ; \quad \psi\text{-scaling variable}$$

In inclusive QE scattering we can observe:

- ☆ Scaling of 1^{st} kind (independence on q)
- ☆ Scaling of 2^{nd} kind (independence on Z)

$\Longrightarrow$ **SuperScaling**

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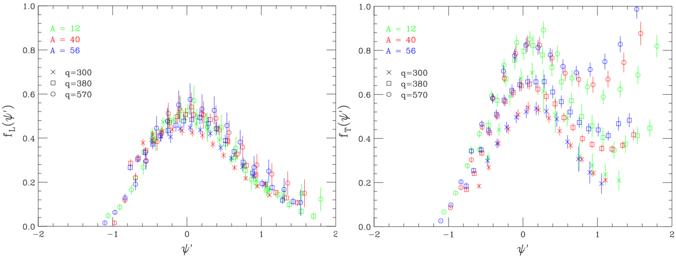


Scaling violations in the T channel $\Rightarrow$ 2p-2h MEC, correlations

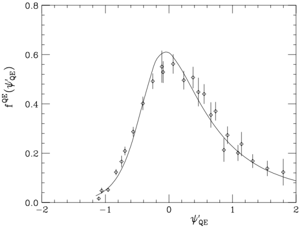
Theoretical description: Scaling phenomenon

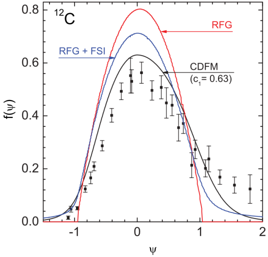
Original SuSA model:

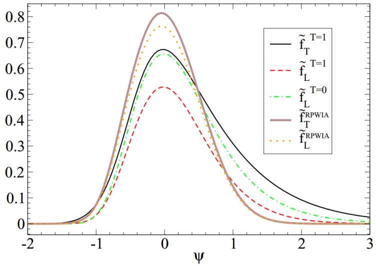
- Fit of the (e, e') longitudinal scaling data
- Assumption $f_L(\psi) = f_T(\psi)$

SuSAv2 *PRC90, 035501, 2014*

- An improved SuperScaling model based on RMF calculations (FSI).
- Decomposition into isoscalar and isovector components which is of interest for CC neutrino reactions.
- RMF & RPWIA models are employed to get a set of scaling functions valid for all lepton-nucleus scattering processes

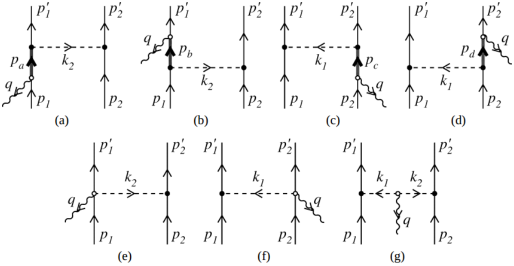






2p-2h MEC for CC neutrino reactions *PRD91, 073004, 2015*

Over 100,000 terms are involved in the calculation, with seven-dimensional integrations



✪ Dekker and De Pace: first attempts for a relativistic description of EM 2p-2h MEC $\Rightarrow$ Extension to the weak sector [PRD 90, 033012 (2014); PRD 90, 053010 (2014)].
✪ The MEC considered are those carried by the pion and by Δ degrees of freedom, the latter being viewed as a virtual nucleonic resonance. All 2p-2h many-body diagrams containing two pionic lines are included. The calculation is performed in the RFG model in which Lorentz covariance can be maintained.
✪ A fully relativistic calculation implies to integrate over the neutrino flux $\Rightarrow$ High increase of the computing time of the nuclear response, involving 7D integrals of thousands of terms $\Rightarrow$ **Parametrization**

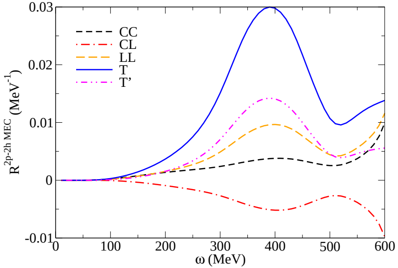
2p-2h MEC parametrization

PRD91, 073004, 2015

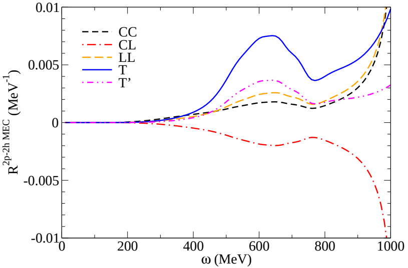
$$R_X^{2p-2hMEC}(\psi', q) = \frac{2a_3 e^{-\frac{(\psi'-a_4)^2}{a_5}}}{1+e^{-\frac{(\psi'-a_1)^2}{a_2}}} + \sum_{k=0}^{2} b_k(\psi')^k$$

$X = CC, CL, LL, T(= T_{VV} + T_{AA}), T'_{VA}$

$a_i(q), b_k(q)$



q=600 MeV/c



q=1000 MeV/c

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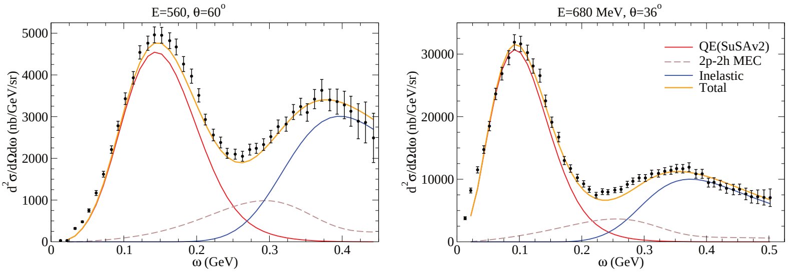
Inclusive $^{12}C(e, e')$ cross sections *PRELIMINARY RESULTS*

Theoretical description beyond the QE peak

➲ Good agreement of SuSAv2 model with (e,e') data
➲ Inelastic RFG model that includes the complete inelastic spectrum ⇒ resonant (Δ), nonresonant, and deep inelastic scattering (DIS). *PRC69, 035502, 2004*
➲ In computing the inelastic hadronic tensor, we employ phenomenological fits of the single-nucleon inelastic structure functions



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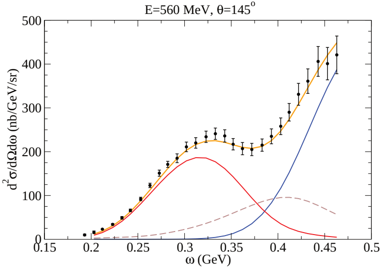

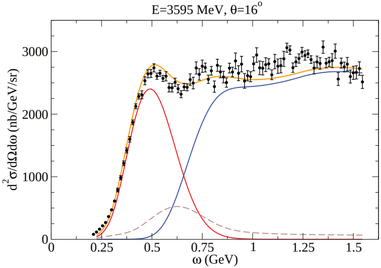

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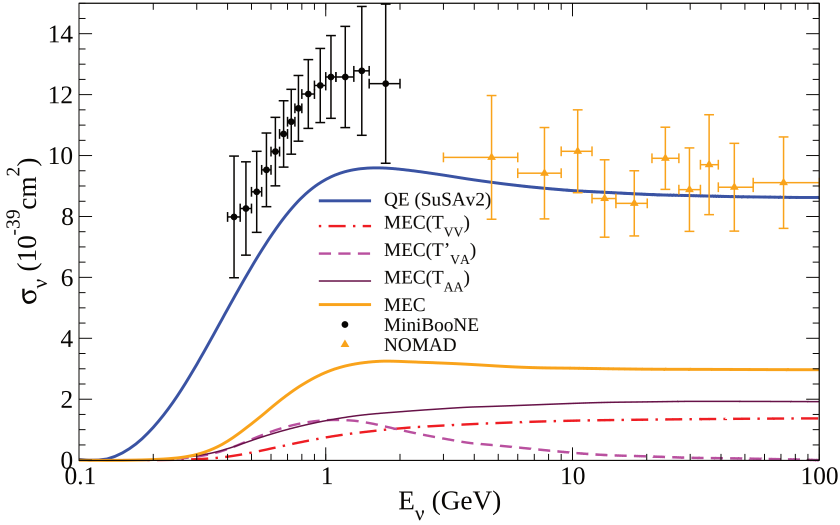
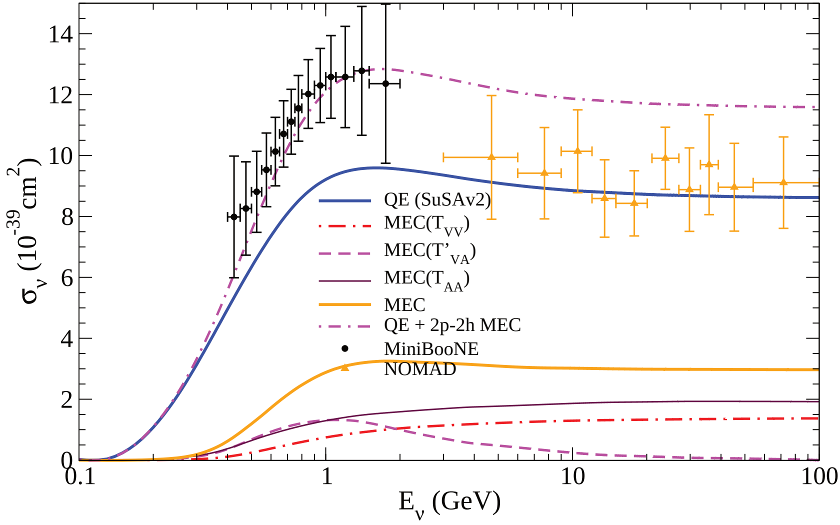
ν_μ-^{12}C CCQE scattering

PRELIMINARY RESULTS



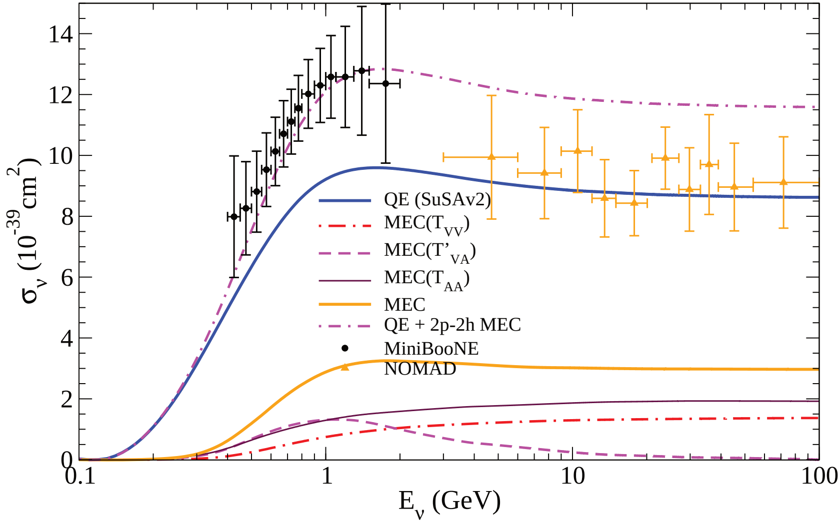
ν_μ-^{12}C CCQE scattering

PRELIMINARY RESULTS



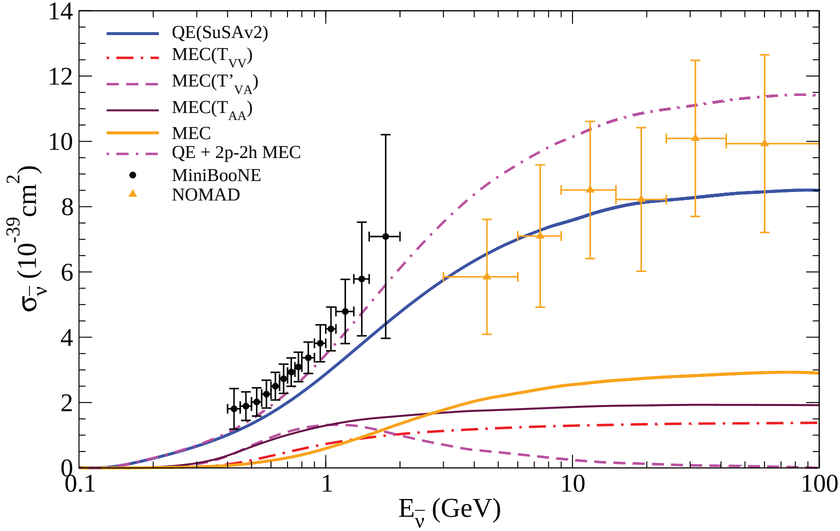
ν_μ-^{12}C CCQE scattering

PRELIMINARY RESULTS

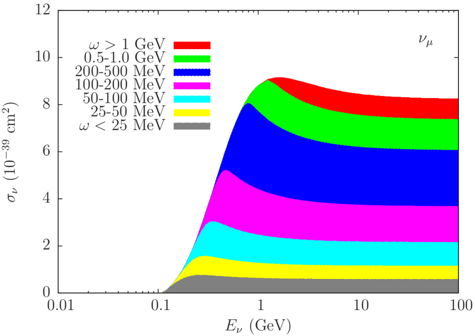


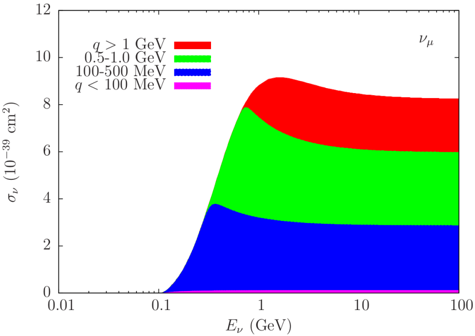
$\bar{\nu}_\mu$-^{12}C CCQE scattering

PRELIMINARY RESULTS



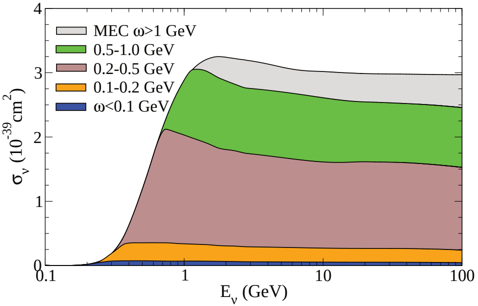
Relevant kinematic regions in the QE cross section

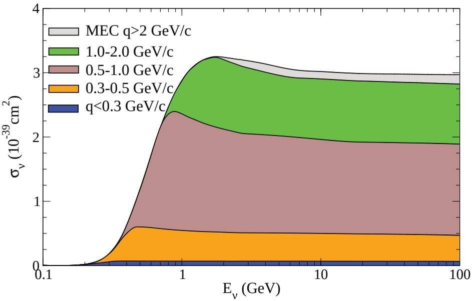




The main contribution to the total QE CS comes from $q < 1$ GeV/c and $\omega < 0.5$ GeV, even at high neutrino energies.

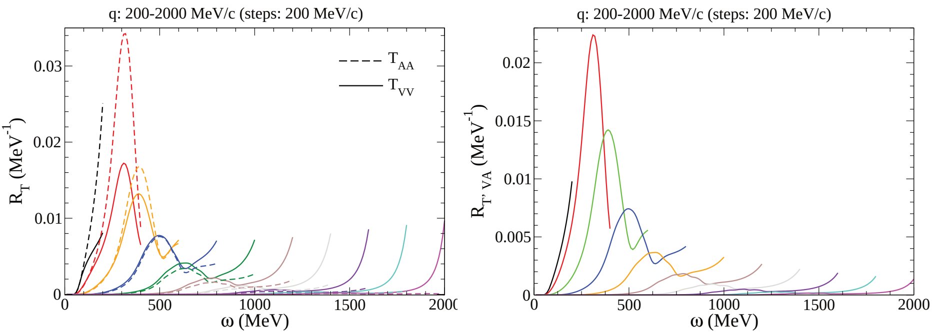
Relevant kinematic regions in the 2p-2h MEC cross section





Although very similar to the QE case, the relevance of 2p-2h MEC contributions extends slightly to higher kinematics.

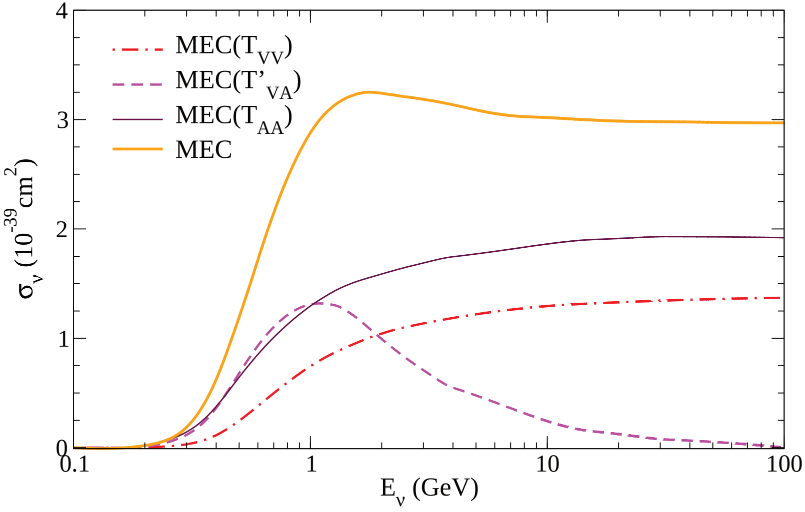
Analysis of 2p-2h MEC vector and axial responses



- T'_{VA} of the same order as T_{VV} and T_{AA}
- Although $T_{VV} > T_{AA}$ at $q > 600$ MeV/c $\Rightarrow \sigma(T_{AA}) > \sigma(T_{VV})$

ν_μ-^{12}C CCQE scattering

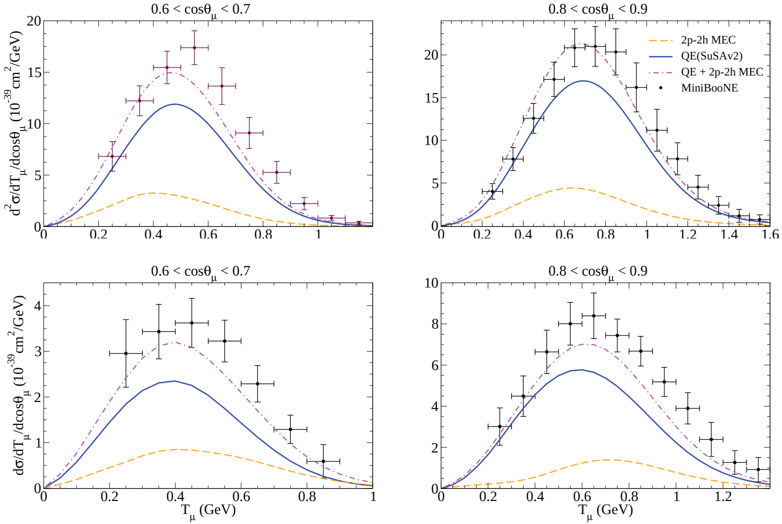
PRELIMINARY RESULTS



MiniBooNE differential cross sections (PRELIMINARY)

$\nu_\mu \Rightarrow$

$\bar{\nu}_\mu \Rightarrow$



Longitudinal 2p-2h MEC effects could improve agreement with data ⇒ Work in progress

Contents

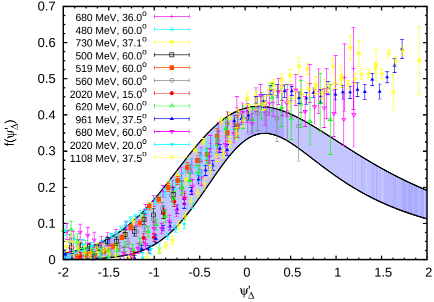
Inclusive total cross section $\Rightarrow$ Δ-scaling model

Extension of the SuSA approach into the non-QE region (arXiv:1506.00801 [nucl-th]), obtained by substracting the QE + 2p-2h MEC contributions from the total cross section $\Rightarrow$ assuming that it is dominated by the Δ-resonance.

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{exp}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{QE,SuSAv2}}_{\mathrm{1p1h}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{MEC}}_{\mathrm{2p2h}}$$

$$f^{\mathrm{non-QE}}(\psi_\Delta) = k_F \frac{\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}}}{\sigma_M(v_L G_L^\Delta + v_T G_T^\Delta)}$$

Scaling works well up to the center of the Δ peak, $\psi_\Delta = 0$, while it breaks at higher energies where other inelastic processes appear $\Rightarrow$ Error band



Inclusive total cross section ⇒ Δ-scaling model

This procedure yields a good representation of the electromagnetic response in both the QE and Δ regions.

$$\left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{non-QE}} = \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{exp}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{QE,SuSAv2}}_{\mathrm{1p1h}} - \left(\frac{d^2\sigma}{d\Omega d\omega}\right)^{\mathrm{MEC}}_{\mathrm{2p2h}}$$

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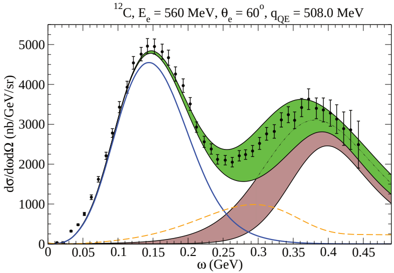
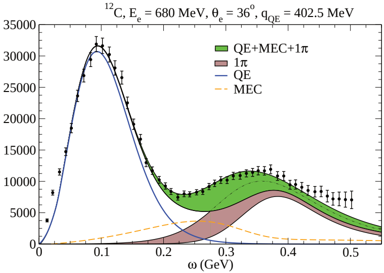
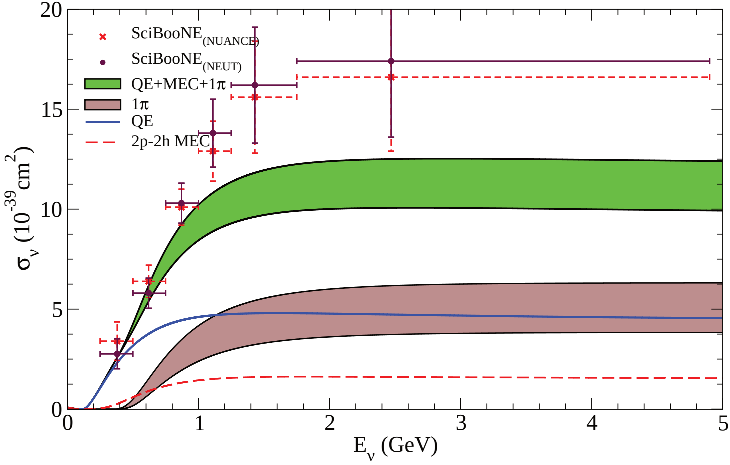




Inclusive total cross section (SciBooNE)

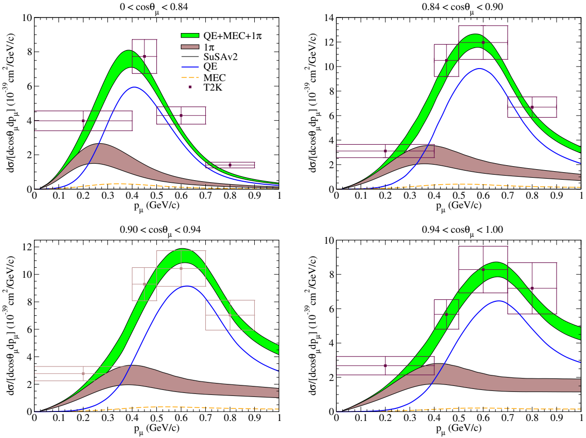
QE+MEC+Δ contributions are not enough to describe inclusive cross section at $E_\nu \gtrsim 1$ GeV ⇒ Work in progress to include DIS in the ν interaction model.



QE+MEC+Δ contributions in $\nu_\mu-^{12}$C scattering

Analysis of T2K data ($<E_\nu>\sim 0.8$ GeV) arXiv:1506.00801 [nucl-th]

➥Deep Inelastic Scattering contributions are not relevant at T2K kinematics.
➥Work in progress to include the DIS description ⇒ analysis of higher-energy data.



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Conclusions and Further Work

➲ The SuSAv2+MEC model has been widely tested against (e,e') data, showing a good agreement with ν-nucleus data from low to high-energy data.

➲ First 2p-2h MEC fully relativistic calculation including direct-exchange interferences in both axial and vector currents.

➲ The inclusion of correlations (positive contribution) and 1p-1h MEC (negative) could improve the agreement with the experimental data.

➲ Extension of the theoretical description of neutrino-nucleus scattering to include Δ and DIS $\Rightarrow$ Complete analysis of all present and future experiments (MINERνA, ArgoNeuT, SciBooNE, etc.)

➲ The possibility of describing the QE and the MEC contributions through a straightforward parametrization might be of interest to Monte Carlo neutrino event simulations used in the analysis of experiments.


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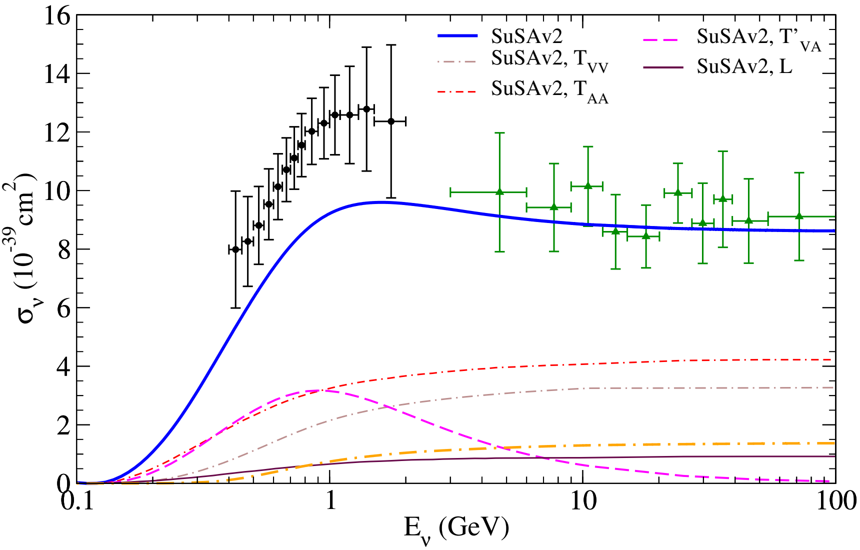
Separated Contributions in the SuSAv2 Model



Theoretical description: Scaling phenomenon

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$\Longrightarrow$ **SuperScaling**

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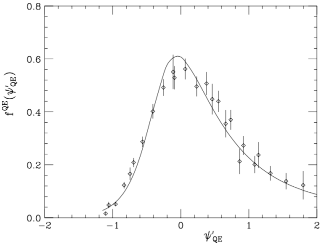
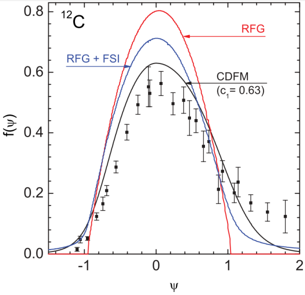
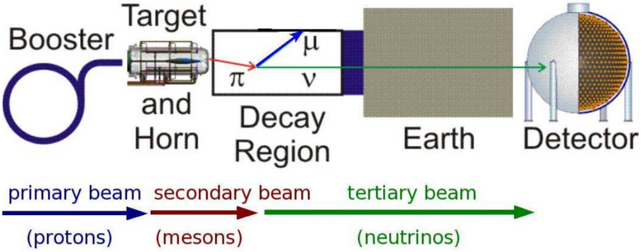




SuSAv2: an improved SuperScaling model based on RMF calculations

Experimental status



Experimental difficulties:

- Determination of the incident neutrino flux, affected by uncertainties of the nuclear model as well as by background processes.
- Extremely reduced cross sections due to weak interactions ($\sim 10^{-6}$ EM) $\Rightarrow$ High experimental accuracy is essential.
- Most of experiments only detects the charged lepton in the final state, not the outgoing nucleon.

Theoretical description: CCQE ν-nucleus cross section

Differential cross section & Scattering matrix amplitude (S_{fi})

$$d\sigma = \frac{|S_{fi}|^2}{T \cdot \Phi_{inc}} dN_f \; ; \; S_{fi} = -i \int d^4X \cdot H_W(X) = -i \left[\frac{g}{2\sqrt{2}}\right]^2 \int j_\mu^{(l)}(X) D_W^{\mu\nu}(X\text{-}Y) J_\nu^{(N)}(Y)$$

Weak leptonic current: $j_\mu = j_\mu^V + \chi j_\mu^A$

$$j_\mu^V = \bar{u}(k')\gamma_\mu u(k)$$
$$j_\mu^A = \bar{u}(k')\gamma_\mu\gamma_5 u(k)$$

Weak hadronic current: $J^\mu = J_V^\mu + J_A^\mu$

$$J_V^\mu = \bar{u}(P')\left[F_1^V\gamma^\mu + \tfrac{i}{2m_N}F_2^V\sigma^{\mu\nu}Q_\nu\right]u(P)$$
$$J_A^\mu = \bar{u}(P')\left[G_A\gamma^\mu + \tfrac{1}{2m_N}G_P Q^\mu\right]u(P)$$

Double differential cross section

$$\left[\frac{d\sigma}{dk_\mu d\Omega}\right]_\chi = \sigma_0 \mathcal{F}_\chi^2 \quad ; \quad \sigma_0 = \frac{\left(G_F^2\cos\theta_c\right)^2}{2\pi^2}\left(k_\mu \cos\frac{\tilde{\theta}}{2}\right)^2 \quad ; \quad \chi = +(-) \equiv \nu_\mu(\bar{\nu}_\mu)$$

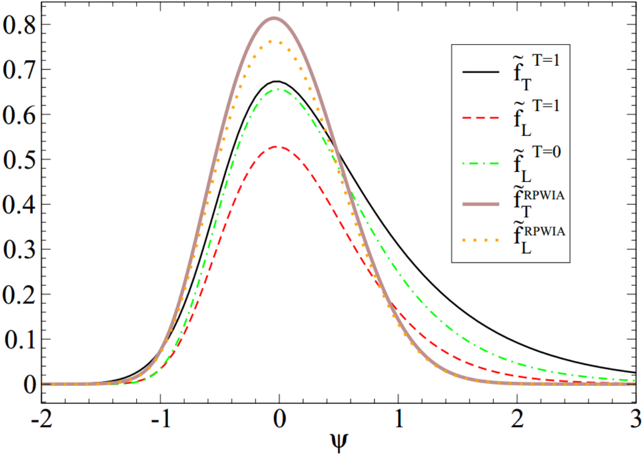
Nuclear structure information

$\mathcal{F}_\chi^2 = \hat{V}_L R_L + \hat{V}_T R_T + \chi\left[2\hat{V}_{T'} R_{T'}\right]$ $\quad L \rightarrow (\mu\nu) = (00, 03, 30, 33)$; $T \rightarrow (11, 22)$; $T' \rightarrow (12, 21)$

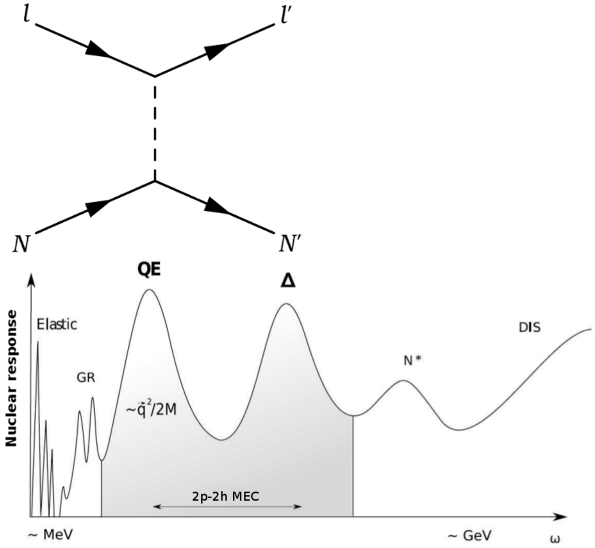
Rosenbluth-like decomposition: $R_L = R_L^{VV} + R_L^{AA}$; $R_{T'} = R_{T'}^{VA}$; $R_T = R_T^{VV} + R_T^{AA}$

Theoretical Description of the SuSAv2 model *PRC90, 035501, 2014*

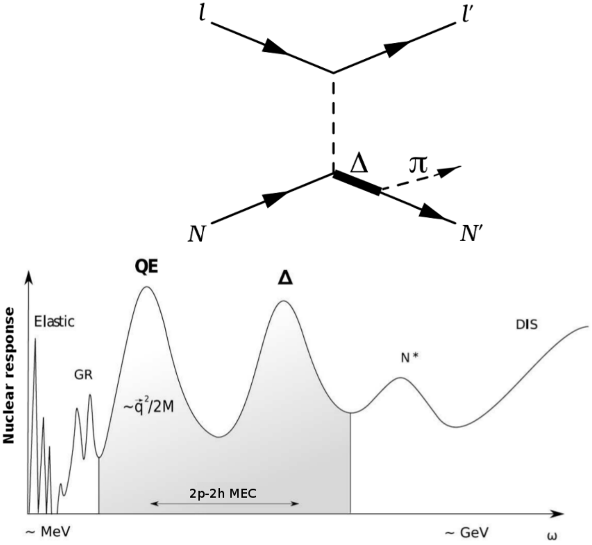
RMF+RPWIA; valid for all lepton-nucleus scattering processes



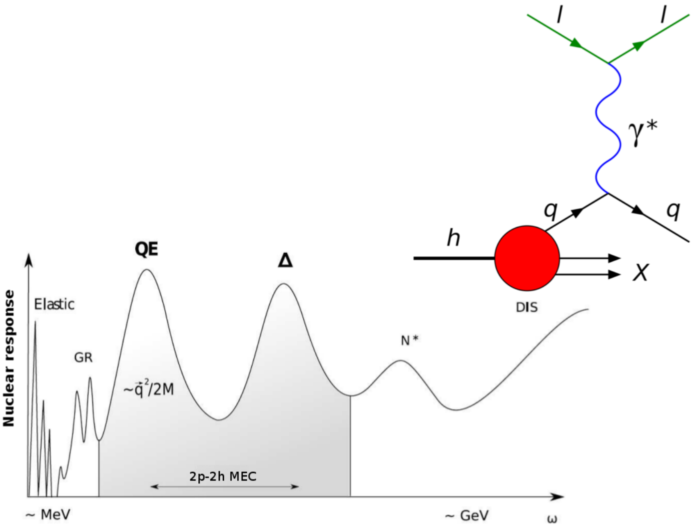
Nuclear response in terms of the energy transfered



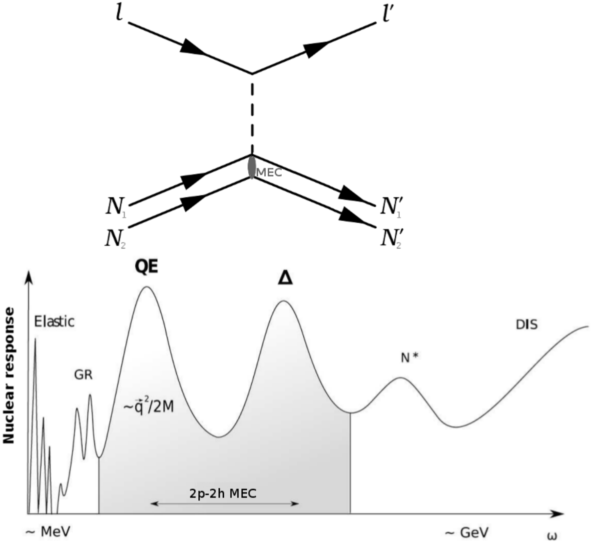
Nuclear response in terms of the energy transfered



Nuclear response in terms of the energy transfered



Nuclear response in terms of the energy transfered



Theoretical Description of the SuSAv2 model *PRC90, 035501, 2014*

Present SuSA

Based on the superscaling function extracted from QE electron-nucleus scattering data.

...

SuSAv2

The Relativistic Mean Field model (RMF) is employed to improve the data analysis, where RMF accounts for FSI.

Longitudinal

Description of nuclear responses built only on the longitudinal scaling function. Assumption of $f_L(\psi) \approx f_T(\psi)$, scaling of 0^{th} kind.

...

Longitudinal + Transversal

Differences between transverse and longitudinal scaling functions are introduced in order to describe properly the nuclear responses.

Isoscalar + Isovector Structure

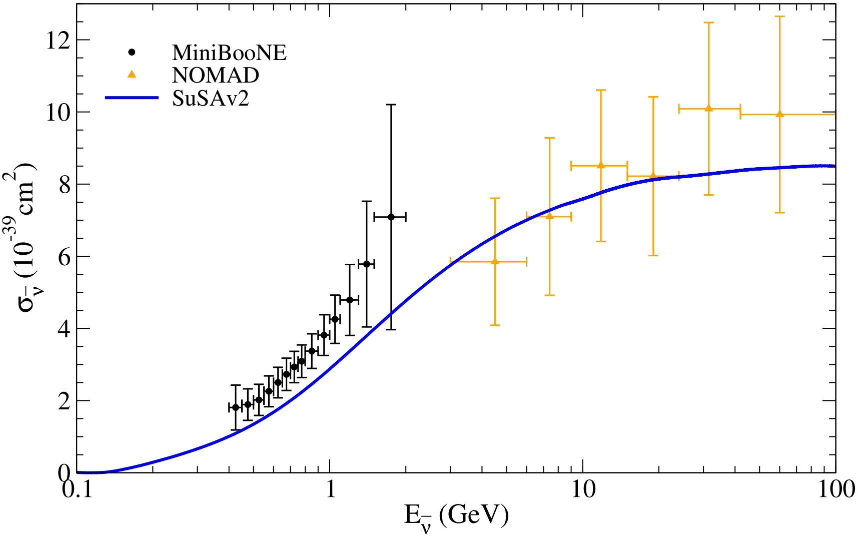
The scaling function based on QE electron scattering data takes into account isovector and isoscalar currents to describe the interaction between the electron and the nucleus.

...

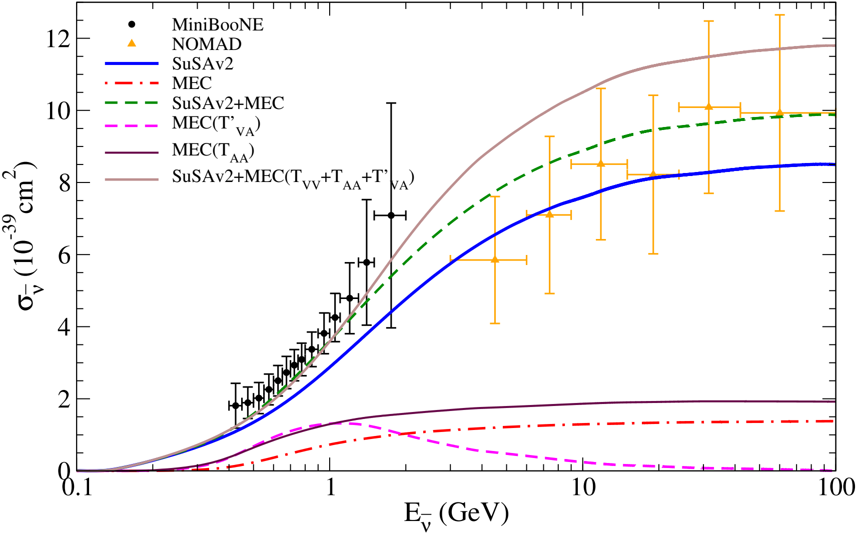
Isovector structure

We separate the scaling function into isovector and isoscalar structure so as to employ a purely isovector scaling function for CCQE neutrino-nucleus processes where isospin changes.

$\bar{\nu}_\mu$-^{12}C CCQE scattering *PRD91, 073004, 2015*



$\bar{\nu}_\mu$-^{12}C CCQE scattering *PRD91, 073004, 2015*



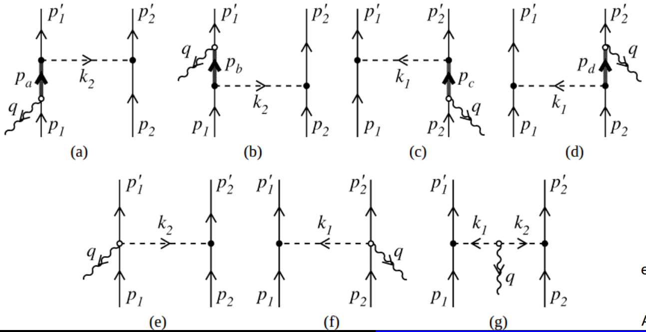
2p-2h MEC contributions

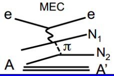
2p-2h MEC comments

Two particle-two hole (2p-2h) states excited through the action of electromagnetic meson exchange currents (MEC) is computed in a fully relativistic framework. The MEC considered are those carried by the pion and by Δ degrees of freedom, the latter being viewed as a virtual nucleonic resonance. The calculation is performed in the relativistic Fermi gas model in which Lorentz covariance can be maintained. All 2p- 2h many-body diagrams containing two pionic lines that contribute to RT are taken into account.

3 main 2p-2h MEC models: Amaro [], Martini [], Nieves []

Over 100,000 terms are involved in the calculation, with seven-dimensional integrations





Experimental status

. . . :

1. The simple description based on a relativistic Fermi gas (RFG) model does not accurately describe the recent measurements of quasielastic neutrino and antineutrino scattering [5-8]. Mechanisms such as nuclear correlations, final-state interactions, and meson-exchange currents (MECs) may have an impact on the inclusive neutrino charged-current (CC) cross section. In particular, explicit calculations support the theoretical evidence [9-11] for a significant contribution from multinucleon knockout to the CC cross sections around and above the quasielastic (QE) peak region. Recent ab initio calculations [12] of sum rules of weak neutral-current response functions of 12C have also stressed the importance of MECs in neutrino quasielastic scattering. The three existing microscopic models that have provided predictions of multinucleon knockout effects in quasielastic neutrino and antineutrino cross sections from 12C for the experimental kinematical settings are those by Martini [14-19], Nieves [10,20-22], and the superscaling analysis (SuSA) model of Refs. [11,23,24].

Experimental status

...:

1. These three models are based on the Fermi gas, but each one contains different ingredients and approximations to face the problem. The Martini model is based on the nonrelativistic model of Ref. [25].The model includes MEC and pionic correlation diagrams modified to account for the effective nuclear interaction. The interference between direct and exchange diagrams is neglected.
2. The Nieves model is similar to Martini?s, but most of it is fully relativistic. In this model, the momentum of the initial nucleon in the generic WNNπ vertex is fixed to an average value. Under this approximation, the Lindhard function can be factorized inside the integral, leaving only a four-dimensional integration over the momentum of one of the exchanged pions. The direct-exchange interference is neglected as well.
3. The SuSA model includes all the interference terms at the cost of performing a seven-dimensional integration, without any approximation, but the axial part of the MEC is not yet included. It is obvious that these three models should differ numerically because they are different. But a quantitative evaluation of their differences has not been done.
4. The first attempts for a relativistic description were made by Dekker [37-39], followed by the model of De Pace et al. [29,40]. The extension of this model to the weak sector requires the inclusion of the axial terms of MEC. Quasielastic neutrino scattering requires one to perform an integral over the neutrino flux. This would considerably increase the computing time of the nuclear response function of Ref. [29] involving 7D integrals of thousands of terms.
5. Two-particle two-hole contributions to electroweak response functions are computed in a fully relativistic Fermi gas, assuming that the electroweak current matrix elements are independent of the kinematics.
6. Why not correlations and not 1p-1h MEC?

Experimental status

Description of QE experimental data

- There is a lot of evidence for a significant multinucleonejection contribution to the inclusive neutrino charge cur-rent (CC) cross section in the 1 GeV energy region [1].On the experimental side, several recent nuclear targetCCQE (CC quasi-elastic) cross section measurements re-ported a large value for the axial mass (MA), in disagree-ment both with older deuterium target measurements [2]and also with electroproduction arguments [3]. A possi-ble explanation for the discrepancy is that some eventsinterpreted as CCQE are in fact due to a different dy-namical mechanism that typically leads to multinucleonemission.
- Understanding of the so-called2 particle-2 hole (2p-2h)effect is an urgent program in neutrino interaction physicsfor current and future oscillation experiments. Such processes are believed to be responsible for the event excesses observedby recent neutrino experiments. The 2p-2h effect is dominated by the meson exchange current (MEC), and is accompaniedby a 2-nucleon emission from the primary vertex, instead of asingle nucleon emission from the charged-current quasi-elastic(CCQE) interaction.Current and future high resolution experiments can potentially nail down this effect. For this reason, there are world wideefforts to model and implement this process in neutrino interaction simulations.
- The inclusive crosssection is the differential cross section as a function of energy transfer. In this space, with moderate electron beamenergy, one can see 2 bumps, representing quasi-elastic (QE) scattering peak and?-resonance peak. These are oftenreasonably modeled, however, many theories fail to reproduce a dip between these 2 bumps. This is the dip region.By adding the MEC, some models successfully reproduce inclusive cross section data including dip region [2]. Thecontribution of MEC is larger in the transverse response than the longitudinal response.Therefore, the importance of MEC is known from electron scattering data. MEC is an interaction involved in 2nucleons, or 2-body current, and it is classified in ?2 particle-2 hole (2p-2h)? effect. Here, a weak boson from theleptonic current is exchanged by a pair of nucleons (2-body current), and believed to lead to 2-nucleon emission.The importance of this process in neutrino interactions wasfirst pointed out by Martiniet al.[3] shortly afterthe MiniBooNE experiment showed their CCQE double differential cross section.

Experimental status

Description of QE experimental data

- Discrepancy between the MiniBooNE data and traditional QE nuclear models $\Longrightarrow$ nuclear correlations, final-state interactions, and meson-exchange currents (MECs) may play an important role.
- Recent calculations [9-12] have stressed the importance of multinucleon knockout and MECs contributions in neutrino QE scattering.
- 3 microscopic models based on RFG predicting multinucleon knockout effects QE $\nu-{}^{12}$C cross sections:

Model	Relativistic	Including
Martini	No	MEC and pionic correlation diagrams. Direct-exchange interference neglect
Nieves	Mostly	Approximation by fixing the initial nucleon in the WNNπ vertex. Direct-exchange interfe
SuSA	Fully	2p-2h MEC but not correlations. Including all interference terms (7D integrat

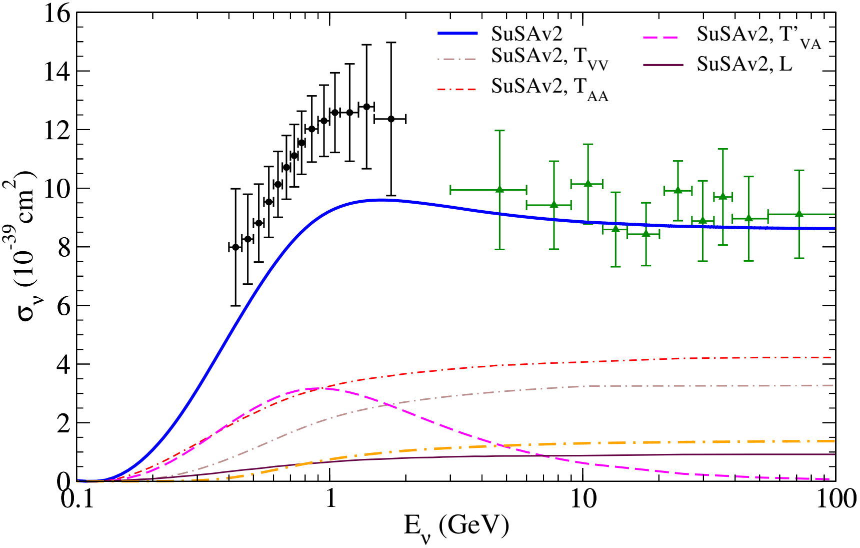
Martini [14-19], Nieves [10,20-22], and the superscaling analysis (SuSA) model of Refs. [11,23,24].

...

...:

1. The first attempts for a relativistic description were made by Dekker [37-39], followed by the model of De Pace et al. [29,40]. The extension of this model to the weak sector requires the inclusion of the axial terms of MEC. Quasielastic neutrino scattering requires one to perform an integral over the neutrino flux. This would considerably increase the computing time of the nuclear response function of Ref. [29] involving 7D integrals of thousands of terms.
2. Two-particle two-hole contributions to electroweak response functions are computed in a fully relativistic Fermi gas, assuming that the electroweak current matrix elements are independent of the kinematics.
3. Why not correlations and not 1p-1h MEC?
4. Two particle-two hole (2p-2h) states excited through the action of electromagnetic/weak meson exchange currents (MEC) is computed in a fully relativistic framework. The MEC considered are those carried by the pion and by Δ degrees of freedom, the latter being viewed as a virtual nucleonic resonance. The calculation is performed in the relativistic Fermi gas model in which Lorentz covariance can be maintained. All 2p- 2h many-body diagrams containing two pionic lines that contribute to RT are taken into account.

Separated QE Contributions in the SuSAv2 Model



MiniBooNE & NOMAD

MiniBooNE (Fermilab) & NOMAD (CERN)

➲ Measurement of CCQE ν_μ ($\bar{\nu}_\mu$) cross sections on a ^{12}C target in the 1 GeV region. Discrepancy between the data and traditional nuclear models.

➲ NOMAD CCQE $\nu_\mu(\bar{\nu}_\mu)-^{12}$C cross sections measurements go from 3 to 100 GeV.

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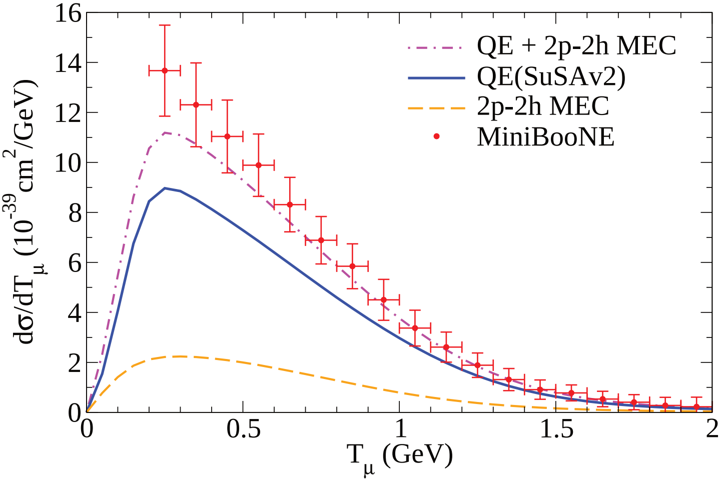
➲ NOMAD CCQE $\nu_\mu(\bar{\nu}_\mu)-^{12}$C cross sections measurements go from 3 to 100 GeV.

Two options to solve this puzzle:

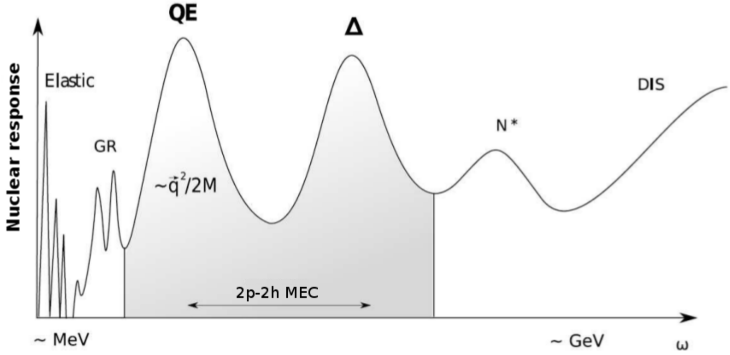
1. MiniBooNE proposed a higher nucleon axial mass value: $M_A = 1.35$ GeV/c^2 $\Longrightarrow$ NOMAD data do not call for a large axial-vector mass (M_A) and do not seem to match with the MiniBooNE results.
2. Microscopic explanations based on multi-nucleon excitations, such as the evaluation of the Meson Exchange Currents (MEC) within the 2p-2h approach $\Longrightarrow$ A consistent evaluation of MEC is hard to achieve.

MiniBooNE differential cross sections (PRELIMINARY)



Longitudinal 2p-2h MEC effects (small contribution) could improve agreement with data ⇒ Work in progress

Experimental status



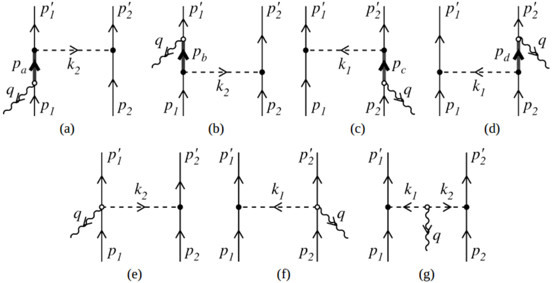
Experimental status EXTENDED

2p-2h effects on the experimental side

- Several recent CCQE cross section measurements have reported a large value for the axial mass (MA), in disagreement both with older deuterium target measurements and also with electroproduction arguments. A possible explanation for the discrepancy is that some events interpreted as CCQE are in fact due to a different dynamical mechanism that typically leads to multinucleon emission (2p-2h MEC, correlations, etc).
- Understanding of the 2p-2h effect is an urgent program in neutrino interaction physics for current and future oscillation experiments. Such processes are believed to be responsible for the event excesses observed by recent neutrino experiments. The 2p-2h effect is dominated by the meson exchange current (MEC), and is accompaniedby a 2-nucleon emission from the primary vertex, instead of asingle nucleon emission from the charged-current quasi-elastic(CCQE) interaction. Current and future high resolution experiments can potentially nail down this effect. For this reason, there are world wide efforts to model and implement this process in neutrino interaction simulations.
- The MEC are also relevant to describe the dip region between the QE and the Delta-resonance peak. The contribution of MEC is larger in the transverse response than the longitudinal one. Therefore, the importance of MEC is well known from electron scattering data. The importance of this process in neutrino interactions was first pointed out shortly after the MiniBooNE experiment showed their CCQE double differential cross section.

2p-2h MEC EXTENDED

Over 100,000 terms are involved in the calculation, with seven-dimensional integrations



✪ The first attempts for a relativistic description were made by Dekker [37-39], followed by the model of De Pace et al. (refs.) only for the vector case (EM) $\Rightarrow$ Extension to the weak sector (Amaro et al. refs.) .
✪ The 2p-2h MEC calculation in a fully relativistic framework implies to integrate over the neutrino flux $\Rightarrow$ High increase of the computing time of the nuclear response function of Ref. [29] involving 7D integrals of thousands of terms $\Rightarrow$ Parametrization
✪ The MEC considered are those carried by the pion and by Δ degrees of freedom, the latter being viewed as a virtual nucleonic resonance. The calculation is performed in the relativistic Fermi gas model in which Lorentz covariance can be maintained. All 2p- 2h many-body diagrams containing two pionic lines that contribute to RT are taken into account.
✪ 2p-2h MEC give a significant contribution to the total cross section $\sim 10-20\%$
✪ RFG model-based calculation, maintaining Lorentz covariance.

PRD91, 073004, 2015

Motivation

Two main related objectives:

1. Complete theoretical description of the inclusive neutrino-nucleus interaction (QE, MEC, Δ-resonance, DIS) and the weak structure of the nucleon.
2. Full analysis of the experimental data in all range of energies from intermediate $E_\nu \sim 1-5$ GeV (MiniBooNE, T2K, MINERνA) to high values $E_\nu \sim$ 10 - 100 GeV (ArgoNeuT, NOMAD).

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Relevance of this investigation:

- To know better the hadronic structure of the nucleon and other nuclear properties such as correlations or 2p-2h MEC.
- To analyze better neutrino oscillations experiments.